Multidipole analysis using a modified parameter search method

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1 Introduction

In magnetoenchephalography (MEG) responses related to higher brain functions, components that cause failure of single equivalent-current-dipole estimation often appear. For example, a single dipole source with a very deep location and very large moment is calculated, which is unacceptable for MEG researchers, although it satisfies the criteria checking the reliability of the dipole, such as goodness-of-fit (GOF) and correlation coefficient. The unacceptable dipole solution is also obtained by multidipole estimation. We have developed a new algorithm to avoid such false solutions and to obtain better accuracy of the source location.

2 Methods

We assumed that MEG responses that cause unacceptably deep dipole solution would be generated by multiple dipoles that have shallower locations and smaller moments than those of the unacceptable dipoles, and that each one of the multiple dipoles would stay at its location during an analysis period. We developed a modified parameter search method for estimating acceptable dipole sources of the MEG responses.

2.1 Parameter search method [1]

The present method is based on the parameter search method [1] consisting of the following five steps:
(1)Defining the cost function,

$$fc = \sum_{i=1}^{N} (Bc_i - Bm_i)^2, \tag{1}$$

where *Bm* and *Bc* are measured and calculated magnetic fields, respectively, and *N* is the number of coils;
(2) determining the initial parameters ($P_1, P_2, \ldots, P_i, \ldots, P_n$) of the dipoles, where P_i is dipole location (x, y, or z coordinate) or moment (strength or direction), and n is the number of parameters;
(3a) calculating cost functions using the parameters in the previous step and using renewed parameters, where parameter renewal is given by changing the P_i to $P_i + jdP_i$ ($j = \pm1, \pm2, \ldots, \pm s_i$, s_i is an integer), selecting the most effective parameter change jdP_i that produces the largest decrease in the cost function;
(3b) changing the parameter increment dP_i *to* dP_i/s_i when the cost functions by all the renewed parameters are greater than those by the previous parameters, and repeating the process (3a); and
(4) stopping the iterative calculation when all of the increments become smaller than a predetermined minimum value.

2.2 Modified parameter search method

In order to avoid false solution, we modified the cost function of the parameter search method to include a term of dipole strength *I* and signal-to-noise ratio (SNR) *S*, which is given by the ratio of the root-mean-squared (RMS) signal fields to RMS noise, as:

$$fc = \sum_{i=1}^{N} (Bc_i - Bm_i)^2 + A \bullet \frac{\sum_{j=1}^{d} I_j^2}{SNR}, \tag{2}$$

where d is the number of dipoles, and A is a coefficient to be determined empirically. In this study, dipole coordinates are fixed during the analysis period. Then, eq. (2) is expanded to

$$Fc = \sum_{i=1}^{L} fc_i, \tag{3}$$

where L is the number of data in the analysis period. In addition to that, the calculation of dipole moments (strength and direction) is separated from that of three coordinates using the Moore-Penrose generalized inverse matrix to improve calculation speed.

3 Simulation

Computer simulations were carried out with calculated and measured magnetic fields to determine coefficient *A* in eq. (2), and to examine the effectiveness of the moment term to avoid deep dipole solution. Further, we examine the dependence of the location error of dipoles on the SNR of simulated MEG responses.

The calculated dipoles were assessed by the following conditions, and those dipoles that satisfied the conditions were selected: (1) GOF larger than 90 %, (2) correlation coefficient larger than 0.95, and (3) conditions 1 and 2 being satisfied for the whole analysis period.

3.1 Magnetic fields for simulation

In this study, two sets of two-dipole sources were assumed in a spherically symmetric conductor, as the original sources. We prepared 30 time-slices of simulated magnetic fields, which are the sum of the magnetic fields produced by the two dipoles and MEG noises measured from the human brain or Gaussian noises. In the calculation of dipole fields [2], the location of them was fixed, and the strength and direction were varied continuously during the time slices. The arrangement of detector coils was the same as that in a 37-ch SQUID magnetometer (BTi). The MEG noises used were prestimulus data of the responses evoked by visual stimuli, measured by the 37-ch SQUID magnetometer, and averaged over 100 trials. Fifteen noises form 5 subjects were used. The Gaussian noises had a root-mean-squared (RMS) amplitude of about 20 [fT].

3.2 Determination of coefficient A in eq. (2)

Two dipoles were estimated for the simulated magnetic fields with an MEG noise (SNR S=7) in the range of A=0 to 140 [(fT/nAm)^2]. Location error, which is the distance between the estimated and original dipoles, and the moment that was averaged during the analysis period of 30 slices are shown in Figs. 1 and 2. For the coefficient A<7[(fT/nAm)^2], a false dipole was about 3 [cm] deeper than the original dipoles and having a moment strength of more than 70 [nAm], were obtained, as shown in Fig. 1. At A=7[(fT/nAm)^2], dipoles with a location error of 0.5 [cm] and moment of 20-30 [nAm] were obtained. At A>7[(fT/nAm)^2], location errors increased and moment decreased with increase in A, as seen in Fig. 2. Therefore, we chose 7 [(fT/nAm)^2] as the coefficient A.

3.3 Efficiency of the moment term in eq. (2)

To examine the efficiency of the moment term in eq. (2), the present method was used for different magnetic fields with MEG and Gaussan noises. Figure 3 shows the location errors for the magnetic fields with MEG noises (α & β) and Gaussian noises (γ & δ) estimated by the two-dipole model with coefficient A=7 [(fT/nAm)^2] and without moment term. SNRs of the magnetic fields were about 7. The results show that for MEG noise α without moment term (A=0), one of the two dipoles became unacceptably deep with a location error of

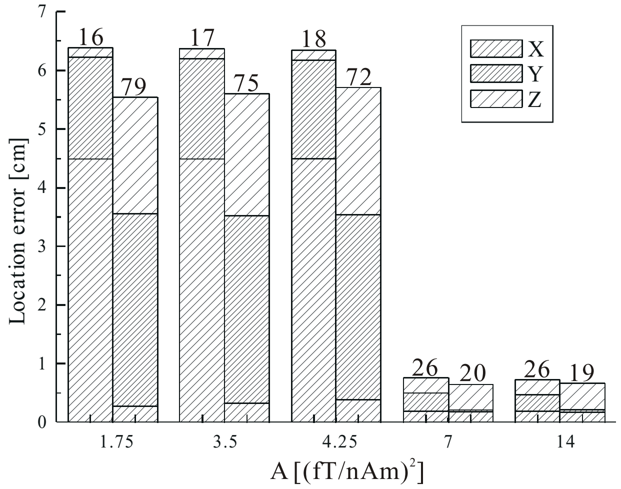


Figure 1: *Estimated dipoles' location error (bar) and moment (value in [nAm] above the bar) for different coefficients A in eq.(2). Two-dipole estimation for simulated magnetic fields with an MEG noise was performed. The Y-coordinate is nearly along the deep-to-shallow direction. At A<7* [(fT/nAm)^2], *one of the two dipoles is located 3 [cm] deeper than the original dipole, and it has a large moment.*

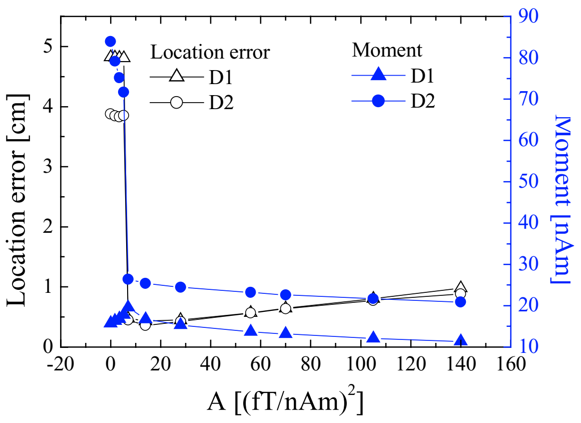


Figure 2: *Location error and moment with different coefficient A in eq. (2) for two dipoles (D1 & D2) calculated by the present method from simulated magnetic fields with an MEG noise.*

more than 3 [cm], but no unacceptable dipole was estimated for other noise even A=0. Therefore, occurrence of unacceptable solution may depend on the distribution of the MEG noise.

3.4 Location error to SNR

The applicability of the present method for various SNRs was examined under the following three conditions: (1) coefficient A=0, (2) A=7 $[(\mathrm{fT/nAm})^2]$ and SNR S fixed at 7, and (3) A=7 $[(\mathrm{fT/nAm})^2]$ and S being varied. Figure 4 shows the obtained location errors as a function of 1/SNR for two sets of original dipoles. Symbols of triangles, solid circles and empty circles in Fig.4 indicate conditions (1), (2), and (3), respectively.

First, the results shown in Fig. 4 (a) are described. The error for condition (3) became smaller than 1 [cm] at 1/SNR<0.5 and further smaller than 0.5 [cm] at 1/SNR<0.1, but the error for conditions (1) and (2) at 1/SNR<0.5 can be as large as 1/SNR>0.5. Therefore, the error for conditions (1) and (2) does not depend on SNR, which may be caused by the local minimum solution. At 1/SNR>0.5, the location error can be larger than 4 [cm] in all three conditions.

Next, the results in Fig. 4 (b), where the locations of original two dipoles are different from that of (a), are described. For conditions (1) and (3), the results are almost the same as those shown in Fig. 4(a). For condition (2), the error at 1/SNR<0.6 became smaller than 1 [cm]. And at 1/SNR<0.1, it was smaller than 0.5 [cm], but lager than that for the condition (3) by 0.3 [cm]. This difference between the conditions (2) and (3) might be caused by the decrease in the amount of the moment term in eq.(2) as SNR increases. These results indicate that the present method enables localization of two dipole sources with an accuracy of 0.5 [cm] at SNR>10.

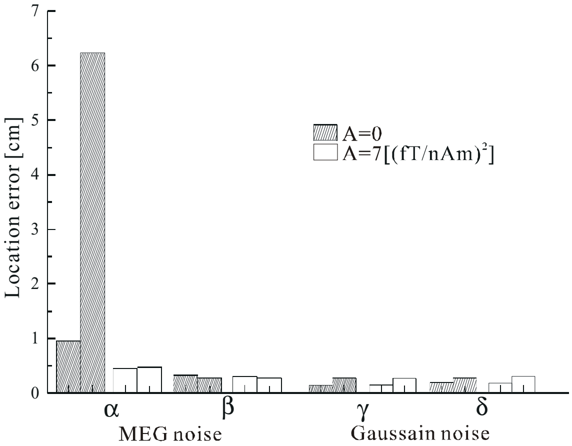
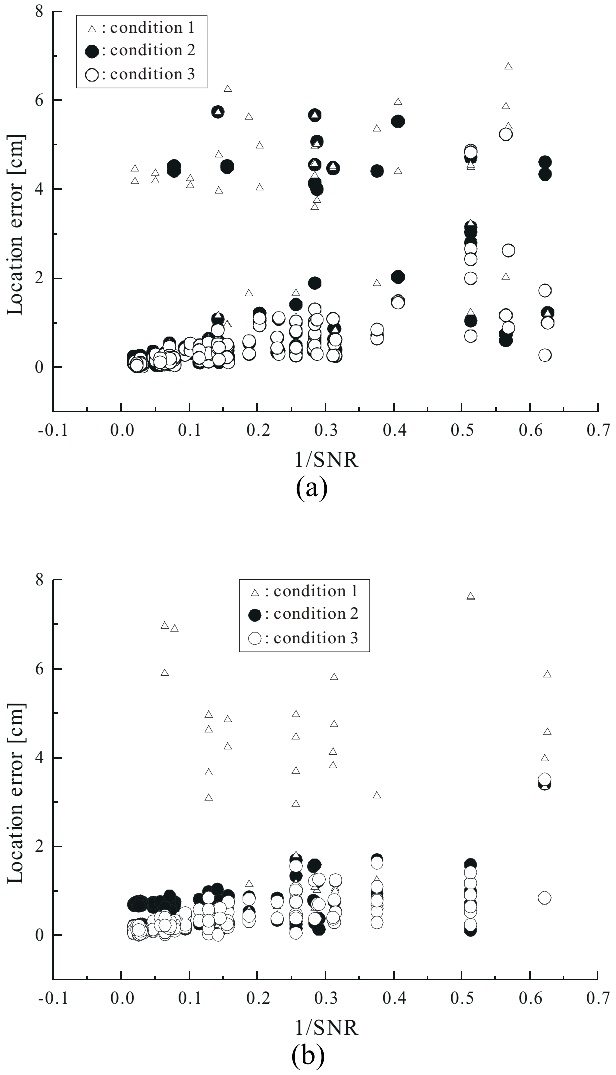


Figure 3: *Dipoles' location error estimated by the present method with coefficient A=7 $[(\mathrm{fT/nAm})^2]$ and 0 in eq.(2) from simulated magnetic fields with MEG noises (α and β) and Gaussian noises (γ and δ).*



(a)

(b)

Figure 4: *Dipoles' location errors as a function of 1/SNR estimated by the present method with coefficient A=0 $[(\mathrm{fT/nAm})^2]$ (triangles: condition 1), A=7 $[(\mathrm{fT/nAm})^2]$ and SNR S fixed at 7 (solid circles: condition 2), and A=7 $[(\mathrm{fT/nAm})^2]$ with S being varied (empty circles: condition 3) from simulated magnetic fields with MEG noises. The location of original two dipoles are different in (a) and (b).*

4 Summary

Including a dipole moment in the cost function to estimate two dipoles was proposed in the previous study [3], but the method was only effective to decrease the moment. In the present method, a term including the moment and SNR was added to the cost function. Two dipoles were successfully localized at the location close to the original ones, from the simulated MEG fields that gave an unacceptably deep solution if the conventional cost function was used. By the present method, possibility of getting unacceptable solutions from the actual MEG responses will be reduced.

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